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High resolution planktic foraminiferal biostratigraphy and correlation across the Palaeocene/Eocene boundary in the Tethys

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Key words. – Biostratigraphy, Foraminifera, Palaeocene, Eocene, Thanetian, Ypresian.

Abstract. – A comparative study of various sections from western Tethys allows us to define a new refined planktic foraminiferal biozonation valid for low and middle latitudes. The classical zones have been recognized along the Palaeocene-Eocene transition, but high resolution methodology allows us to define new subzones, especially within the Palaeocene-Eocene boundary interval. The planktic foraminiferal faunal turnover across the P/E boundary is gradual with the exception of an acarininid diversification and their excursion toward higher latitudes. *Acarinina berggreni* is the first acarininid to evolve during the P/E event, whereas the first appearance of other acarininid species (*Acarinina sibaiyaensis, Acarinina africana* and *Acarinina quetra*) occurred at or just above a dissolution clay layer present in most of the deep sea sections. The extinction of the bathyal and abyssal small benthic foraminifera occurred just below the dissolution clay interval in the *A. berggreni* Subzone and constitutes an apparently isochronous datum. The isotopic and planktic foraminiferal excursions began at the base of the *Acarinina berggreni* Subzone and ended at the top of the *Acarinina sibaiyaensis* Subzone.

Biostratigraphie à haute résolution basée sur les foraminifères planctoniques et corrélation autour de la limite Paléocène/Eocène dans le domaine téthysien

Mots clés. – Biostratigraphie, Foraminifères, Paléocène, Eocène, Thanétien, Yprésien.

Résumé. – L'étude comparée de plusieurs coupes de la Téthys occidentale nous permet d'établir une nouvelle biozonation détaillée à partir des foraminifères planctoniques, valable pour les basses et moyennes latitudes. Les zones classiques ont été reconnues à la transition Paléocène-Eocène, mais un échantillonnage à haute résolution nous permet de définir de nouvelles sous-zones. Le renouvellement des foraminifères planctoniques à la limite P/E est progressif, sauf pour la diversification des acarininidés et leur excursion vers les latitudes plus élevées. *Acarinina berggreni* est la première acarininidé à évoluer durant l'événement de la limite P/E, alors que les premières apparitions des autres espèces d'acarininidés *(Acarinina sibaiyaensis, Acarinina africana* et *Acarinina quetra)* se produisirent au niveau, ou immédiatement au-dessus, d'une couche d'argile de dissolution présente dans la plupart des coupes de mer profonde. L'extinction des foraminifères bathyaux et des petits foraminifères abyssaux se produisit juste sous l'intervalle de l'argile de dissolution, dans la sous-zone à *A. berggreni,* et constitue apparemment un repère isochrone. L'excursion isotopique et celle des foraminifères planctoniques débuta à la base de la sous-zone à *Acarinina berggreni* et se termina au sommet de la sous-zone à *Acarinina sibaiyaensis.*

VERSION FRANÇAISE ABRÉGÉE

La limite Paléocène/Eocène (P/E) n'a pas encore été définie et la désignation d'une coupe de référence (*global stratigraphic section and point* – GSSP) reste en attente. La limite sera probablement placée au niveau, ou immédiatement au-dessus, de l'extinction des foraminifères benthiques (*benthic foraminiferal extinction event* – BFEE), qui est marquée par des changements importants (excursions) dans la composition des isotopes stables du carbone et de l'oxygène. Dans le but de positionner et corréler les événements majeurs autour de la limite P/E, nous avons étudié les assemblages de foraminifères planctoniques de différentes coupes de la Téthys et présenté les premiers résultats lors de la réunion de la SGF sur la limite Paléocène/Eocène tenue à Paris en 1998 [Molina *et al.*, 1998]. Cette étude nous a permit de réviser et mettre à jour la zonation biostratigraphique des foraminifères planctoniques, de proposer un nouveau découpage en sous-zones et de suggérer une corrélation entre les coupes et autres événements géochimiques sur la base de l'échelle géochronologique de Berggren *et al.* [1995].

De nombreuses coupes ont été étudiées en Belgique, golfe de Gascogne, France, Israël, Italie, Kazakhstan, Espagne et Tunisie. Les meilleures coupes ont été étudiées en détail et nos résultats sont résumés dans cette note. Les dix meilleures coupes étudiées sont situées en Espagne (Alamedilla et Caravaca dans la Cordillère bétique et Zumaya, Campo et Tremp dans les Pyrénées), en golfe de Gascogne (DSDP Site 401), en Italie (Bottaccione et Possagno), en Israël (Ben Gurion) et au Kazakhstan (Kaurtakapy) (fig. 1).

Notre étude comparative et à haute résolution des populations de foraminifères planctoniques dans les coupes de la Téthys occidentale nous permet d'identifier plusieurs événements biostratigraphiques autour de la transition Paléocène-Eocène (chrones C24 and C25), événements que nous utilisons pour améliorer la biostratigraphie autour de la transition P-E en définissant de nouvelles sous-zones (fig. 2). Ces sous-zones sont valables pour les basses et moyennes latitudes du domaine de la Téthys et devraient pouvoir être appliquées aux latitudes similaires autour du globe.

Certaines des coupes étudiées sont pauvres en foraminifères planctoniques, en raison de leur faciès peu profond ; il en est ainsi des coupes de Oued Mezez (Tunisie), Knokke (Belgique), Zomet Telalim (Israël) et Tremp (Espagne) pour lesquelles une biostratigraphie haute résolution sur la base des foraminifères est donc difficile à appliquer. A Oued Mezez par exemple, sur la bordure méridionale de la Téthys, des faciès phosphatés de plate-forme peu profonde correspondent à la transition P-E. Les corrélations entre les dix meilleures coupes étudiées, avec indication de l'épaisseur des différentes biozones, des hiatus déduits et d'autres caractéristiques en relation avec l'échelle biostratigraphique et chronostratigraphique sont donnés dans la figure 2.

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La coupe d'Alamedilla est probablement la mieux exposée et la plus continue des coupes espagnoles connues à ce jour. La conservation du matériel n'y est pas aussi bonne qu'à Caravaca, mais les foraminifères planctoniques y sont abondants, ce qui permet une biostratigraphie détaillée [Arenillas et Molina, 1996] qui a été corrélée avec les changements dans les compositions isotopiques et les assemblages minéralogiques [Lu *et al.*, 1996; Arenillas *et al.*, 1996; Molina *et al.*, 1996a; Pardo et Arenillas, 1996]. Toutes les sous-zones de *M. soldadoensis* à *M. formosa* sont présentes et il n'y pas d'évidence de hiatus dans la zone de transition P-E. L'extinction des foraminifères benthiques (BFEE) est surmontée par un niveau d'argile rouge qui est lui-même surmonté par l'excursion hors des tropiques des foraminifères planctoniques (fig. 3). Les nannofossiles et la magnétostratigraphie sont en cours d'étude.

La coupe de Zumaya est une coupe épaisse, où la biozone à *M. subbotinae* est particulièrement bien développée, formée d'environ 120 m de marnes et de grès calcaires. Néanmoins, la transition P-E est marneuse et peu développée. Von Hillebrandt [1965] fut le premier à publier la biostratigraphie des foraminifères planctoniques de cette coupe. Les assemblages de foraminifères planctoniques, le renouvellement des faunes et la bio-chronostratigraphie de la transition P-E on été étudiés par Canudo et Molina [1992a], Canudo *et al.* [1995] et Molina *et al.* [1996b]. Une étude à haute-résolution des teneurs en iridium, des compositions en isotopes stables et des correlations avec les nannofossiles et les foraminifères a été conduite par Schmitz *et al.* [1997]. Cette coupe est la coupe continue en domaine marin profond la plus épaisse connue à ce jour. La sous-zone à *A. berggreni* a presque 2 m d'épaisseur et la sous-zone à *A. sibaiyaensis* a environ 4 m d'épaisseur (fig. 4).

Les premières études de micropaléontologie de la coupe de Possagno (Italie) ont été résumées dans une monographie dans laquelle Luterbacher [1975] étudia les foraminifères planctoniques. Cette coupe classique d'Italie est située dans une carrière, ce qui limite sa valeur comme candidate pour un stratotype de la limite P/E. En outre, cette coupe est très condensée avec un niveau d'argile sombre de 4 cm d'épaisseur et la zone à *Morozovella velascoensis* n'a qu'environ 1 m d'épaisseur. Néanmoins, nous y avons reconnu toutes les sous-zones depuis *M. gracilis* à *P. wilcoxensis*. L'excursion des acarinidés hors des tropiques y est très évidente et coïncide avec le changement du $\partial^{13}C$ [Arenillas *et al.*, 1999] (fig. 5).

La corrélation des coupes ne présente pas de difficulté et la biostratigraphie de haute résolution nous a permis de reconnaître plusieurs hiatus (fig. 2). La séquence sédimentaire générale autour de la limite P/E consiste en une unité détritique *(lowstand systems tract),* de marnes et d'argilites *(transgressive systems tract)* et de calcaires marneux *(highstand systems tract)*, bien que l'unité détritique basale, située dans la sous-zone à *M. gracilis,* n'existe pas dans les coupes distales condensées comme celle de Possagno [Arenillas *et al.*, 1999].

La nouvelle sous-zonation est valable pour les latitudes sub-tropicales et tempérées dans lesquelles les acarininidés et morozovellidés sont fréquents. L'ordre d'apparition et de disparition des espèces a été établi en fonction de la distribution stratigraphique maximale de chaque espèce, en prenant en compte toutes les coupes étudiées (fig. 6). La nouvelle sous-zonation pour la transition P-E est facilement identifiable dans les coupes pélagiques profondes d'Espagne, d'Italie, de Tunisie et d'Israël. Par contre, il est plus difficile de l'appliquer aux coupes du domaine boréal comme celle de Kaurtakapy (Kazakhstan) dans la Paratéthys septentrionale. Dans les coupes des latitudes plus élevées la plupart des acarininidés et morozovellidés sont uniquement présents dans l'intervalle de l'excursion hors des tropiques coïncidant avec une élévation de la température. Par conséquent, plus la latitude est élevée, moins cette biozonation est applicable.

INTRODUCTION

The Palaeocene/Eocene boundary (P/E) has not been defined and still awaits identification of a global stratigraphic section and point (GSSP). The boundary will be probably placed at or shortly above the benthic foraminiferal extinction event (BFEE), which is marked by prominent shifts in carbon and oxygen stable isotopes [Letolle and Renard, 1980; Stott and Kennett, 1990; Schmitz *et al.*, 1996, 1997]. This seems to be the most relevant event in the Palaeocene-Eocene transition and the most plausible explanation appears to lie in the reorganization of tectonic plates [Berggren and Hollister, 1974; Rea *et al.*, 1990] that produced a period of intensive volcanic activity [Knox and Morton, 1988]. This may have generated a strong release of CO_2 which oxidized producing methane [Sloan *et al.*, 1992] and a blast of gas due to massive dissociation of oceanic methane hydrate [Dickens *et al.*, 1997]. The effects were greenhouse, global warming, changes in oceanic temperature and circulation [Kennett and Stott, 1990; 1991; Owen and Rea, 1992] and rise of the lysocline producing $CaCO_3$ dissolution at bathyal depths [Molina *et al.*, 1994; Canudo *et al.*, 1995; Dickens *et al.*, 1997]. All these factors combined may have caused the mass extinction of the bathyal and abyssal small benthic foraminifera [Tjalsma and Lohman, 1983; Miller *et al.*, 1987; Thomas, 1990; Kennett and Stott, 1991; Speijer *et al.*, 1996] and a rapid diversification of acarininids (planktic foraminifera) that expanded toward higher latitudes [Berggren and Olsson, 1986; Canudo and Molina, 1992a; Molina *et al.*, 1994; Kelly *et al.*, 1996; Pardo *et al.*, 1999].

The P/E boundary has been tentatively placed by some planktic foraminifera specialists at the first occurrence (FO) of *Pseudohastigerina wilcoxensis* [Berggren *et al.*, 1967] or at the last occurrence (LO) of *Morozovella velascoensis* [Bolli, 1957; Stainforth *et al.*, 1975; Toumarkine and Luterbacher, 1985]. According to Berggren *et al.* [1995] the P/E boundary is bracketed by the LO of *Morozovella velascoensis* and the BFEE, and encompasses the NP9/NP10 calcareous nannofossil zonal boundary at about 55 Ma and the base of the London Clay Formation. These events are close to the base of the Ypresian Stage [Aubry *et al.*, 1988; Dupuis *et al.*, 1988; Schuler *et al.*, 1992; Pardo *et al.*, 1994] and within the lower part of the Ilerdian Stage [Cavelier and Pomerol, 1986; Molina *et al.*, 1992; Molina, 1994, 1996; Serra-Kiel *et al.*, 1994].

In order to precisely place and correlate the main events across the P/E boundary we have conducted a study of planktic foraminiferal assemblages of various sections in the Tethys that was first presented at the P/E meeting in Paris [Molina *et al.*, 1998]. This study allows us to revise and update the planktic foraminiferal biostratigraphical zonation, to propose a new high resolution subzonation and to suggest a correlation among sections, geochemical events and within the framework of the geochronological scale of Berggren *et al.* [1995].

MATERIALS AND METHODS

In search for a suitable Palaeocene/Eocene boundary stratotype many sections were studied in Belgium, Bay of Biscay, France, Israel, Italy, Kazakstan, Spain and Tunisia. The best ten sections were studied at higher resolution and their results are summarized in this paper. Other sections, such as the Ypresian stratotype in Belgium [Pardo *et al.*, 1994] and the Oued Mezez section in Tunisia [Arenillas, 1996], are poor in planktic foraminiferal and were not included in this synthesis, although their results were taken into consideration. The best ten studied sections are located in Spain (Alamedilla and Caravaca in the Betic Cordillera and Zumaya, Campo and Tremp in the Pyrenees), the Bay of Biscay (DSDP Site 401), Italy (Bottaccione and Possagno), Israel (Ben Gurion) and Kazakstan (Kaurtakapy) (fig. 1).

All sections were sampled in detail and at higher resolution across the P/E event, taking the samples more closely than previous authors. Samples spacing in each case depended on the thickness of the section, in the more condensed sections samples were taken at centimetre intervals and in the more expanded sections at meter intervals. Nevertheless, in all sections the P/E boundary event was sampled at centimetre intervals.

Samples were diluted in H_2O_2, washed in tap water using a 63 microns sieve and the planktic foraminiferal residue was dried in an oven at 50 degrees centigrades. Most of the samples were studied quantitatively. Representative splits were obtained using a modified Otto microspliter of about 300 or more specimens. All the representative specimens were classified and mounted on microslides. The rest of the residue was scanned searching for rare specimens.

BIOSTRATIGRAPHY

Previous biozonations [i.e., Bolli, 1957; Canudo and Molina, 1992b; Berggren *et al.*, 1995] were not detailed enough to solve some of the chronostratigraphic problems related to the P/E boundary. Arenillas and Molina [1996] proposed the *Igorina laevigata* Zone for the lower part of the *Morozovella velascoensis* Zone as an attempt to increase the biostratigraphic resolution across the P/E boundary, but these authors have decided not to use this zone any further since *I. laevigata* is a rare morphotype and may be a junior synonym of *Igorina albeari* according to Blow [1979] and Berggren and Norris [1997]. Furthermore, Pardo *et al.* [1999] proposed a subdivision of Zone P5 of Berggren *et al.* [1995] based on the FO of *Acarinina sibaiyaensis* and/or *Acarinina africana*.

Our current comparative and high resolution study of the planktic foraminiferal populations in the western Tethys area allows us to identify several datum events in the P-E transition (chrons C24 and C25). These events have been used to further improve the P-E transition biostratigraphy with the definition of new subzones (fig. 2), valid for low and middle latitudes across the Tethys that might be applied to similar latitudes worldwide.

Luterbacheria pseudomenardii Zone

Biostratigraphic interval of the total range of the nominate taxon.

It was defined by Bolli [1957] and is equivalent to Zone P4 of Berggren *et al.* [1995]. The base of this zone has not been considered in this paper since it occurs in Chron C26r. This zone has been divided into the following subzones (from botton to top).

– *Luterbacheria pseudomenardii* Subzone. – Biostratigraphic interval from the first occurrence (FO) of *L. pseudomenardii* to the FO of *Muricoglobigerina soldadoensis*. This subzone is equivalent to Zone P4 of Blow [1979] and to Subzones P4a and P4b defined by Berggren *et al.* [1995]. We were not able to recognise a subdivision into Subzones P4a and P4b since the last occurrence (LO) of *Acarinina subsphaerica* in Alamedilla, Caravaca, Zumaya and Possagno occurs above the LO of *L. pseudomenardii*. In this subzone *Muricoglobigerina chascanona, Chiloguembelina wilcoxensis, Parasubbotina pseudoimitata, Morozovella dolabrata, Acarinina subsphaerica* and *Morozovella edgari* first appear and *Luterbacheria ehrenbergi* and *Morozovella kolchidica* disappear.

– *Muricoglobigerina soldadoensis* Subzone. – Biostratigraphic concurrent interval from the FO of *M. soldadoensis* to the LO of *L. pseudomenardii*. This subzone is equivalent to Subzone P4c defined by Berggren *et al.* [1995]. In this

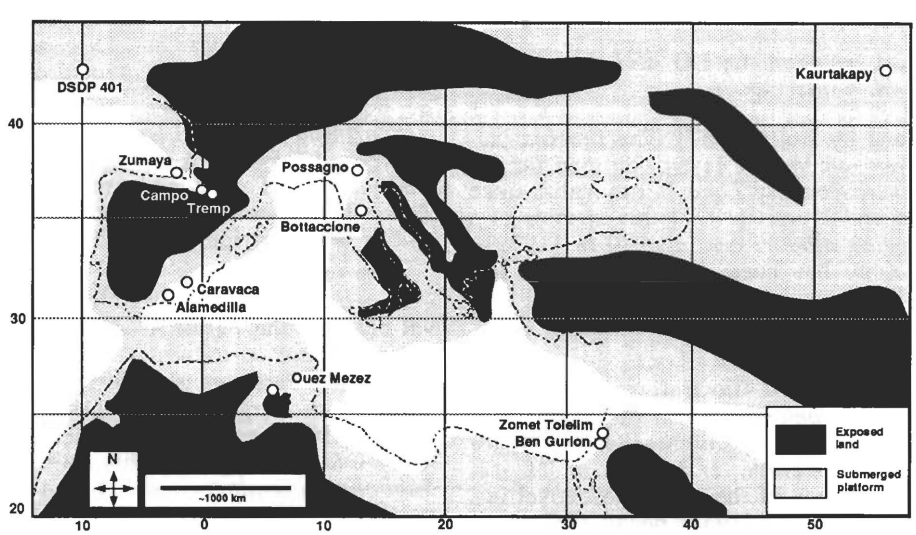

FIG. 1. – Geographic and palaeogeographic location of the sections studied [modified from Denham and Scotese, 1987].

FIG. 1. – *Localisation géographique et paléogéographique des coupes étudiées [modifié de Denham et Scotese, 1987].*

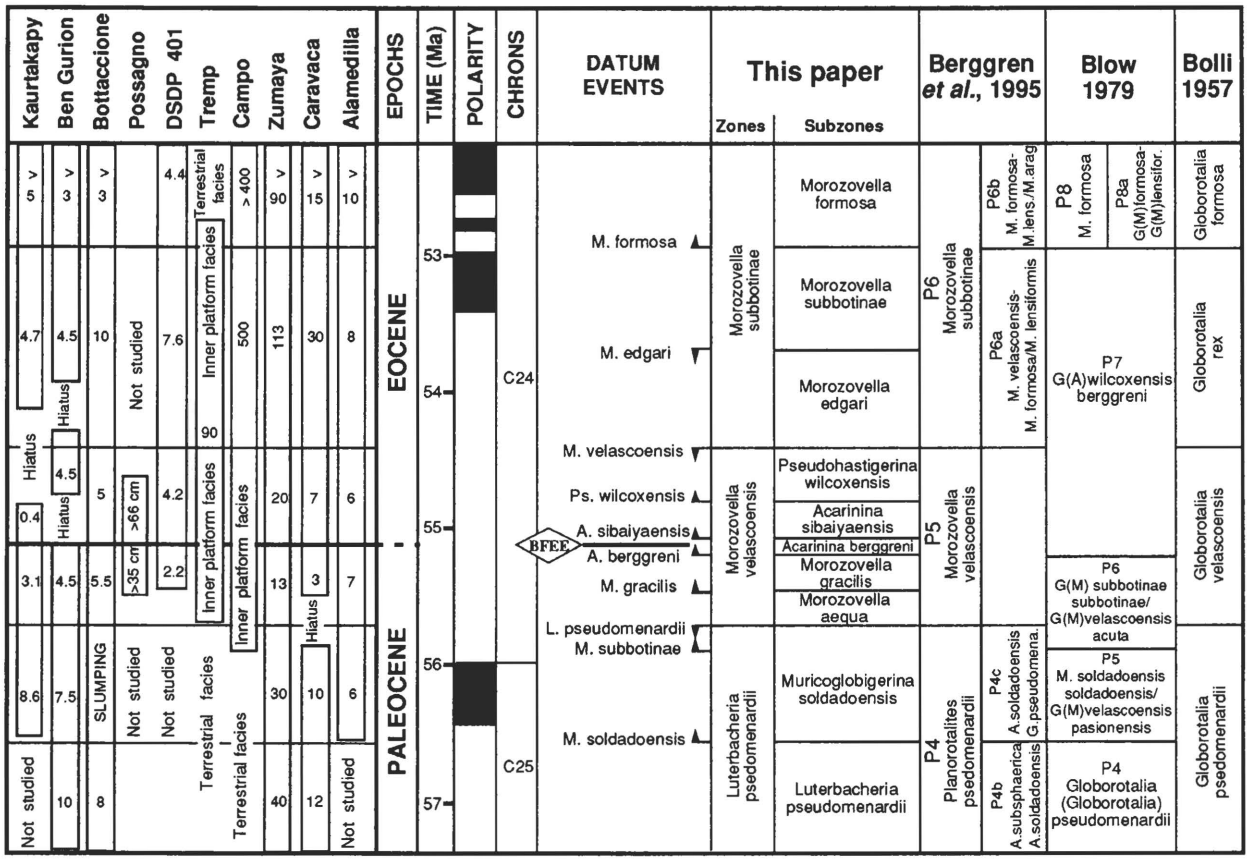

FIG. 2. – Correlation of the main biozonations, geochronological scale and best ten sections studied.

FIG. 2. – *Correlation des principales biozonations, échelle geochronologique et dix meilleures coupes étudiées.*

subzone *Chiloguembelina strombiformis, Luterbacheria elongata, Igorina lodoensis, Muricoglobigerina esnehensis, Morozovella subbotinae, Subbotina incisa* and *Luberbacheria capdevilensis* first appear and *Parasubbotina quadrilocula* disappears.

Morozovella velascoensis Zone

Biostratigraphic interval between the LO of *L. pseudomenardii* and the LO of *M. velascoensis*.

This zone was defined by Bolli [1957]. The *Igorina laevigata* Zone of Arenillas and Molina [1996] defined for the lower part of the *M. velascoensis* Zone is not valid since according to Berggren and Norris [1997] this species is a junior synonym of *Igorina albeari* (see also Blow [1979]). The *M. velascoensis* Zone has been divided into the following subzones.

– *Morozovella aequa* Subzone. – Biostratigraphic interval between the LO of *L. pseudomenardii* and the FO of *Morozovella gracilis*. It was defined by Luterbacher [1964] for identifying the interval above the extinction of *M. velascoensis* up to the appearance of the other morozovellids, an interval not identified by Bolli [1957] because of a hiatus. It was modified by Canudo and Molina [1992a,b] and in this paper has been restricted to its lower part. In this subzone *Morozovella marginodentata* has its initial appearance and *Muricoglobigerina mckannai, M. conicotruncata, Acarinina nitida, Morozovella angulata, Acarinina subsphaerica* and *Globanomalina haunsbergensis* disappear.

– *Morozovella gracilis* Subzone. – New subzone herein defined. Biostratigraphic interval between the FO of *M. gracilis* and the FO of *Acarinina berggreni*. In this subzone *Chiloguembelina circumlabiata, Chiloguembelina multicerallis, Muricoglobigerina angulosa,* and *Muricoglobigerina senni* first appear and *Luterbacheria troelseni, Igorina pusilla* and *Morozovella acutispira* disappear.

– *Acarinina berggreni* Subzone. – Biostratigraphic interval between the FO of *A. berggreni* and the FO of *Acarinina sibaiyaensis*. This zone was defined by Blow [1979] as Zone P7 *Globorotalia (Acarinina) wilcoxensis berggreni* and is here restricted to its lowermost part.

– *Acarinina sibaiyaensis* Subzone. – Biostratigraphic interval between the FO of *A. sibaiyaensis* and the FO of *Pseudohastigerina wilcoxensis*. This subzone was originally defined by Pardo *et al.* [1999], proposing a subdivision of Zone P5 of Berggren *et al.* [1995] into two subzones: P5a and P5b based on the FO of *Acarinina sibaiyaensis* and/or *Acarinina africana*. In this subzone *Acarinina africana, Subbotina pseudoeocaena,* and *Acarinina quetra* first appear and *Igorina albeari* disappears.

– *Pseudohastigerina wilcoxensis* Subzone. – Biostratigraphic interval between the FO of *P. wilcoxensis* and the LO of *M. velascoensis*. It was defined by Berggren [1971], it

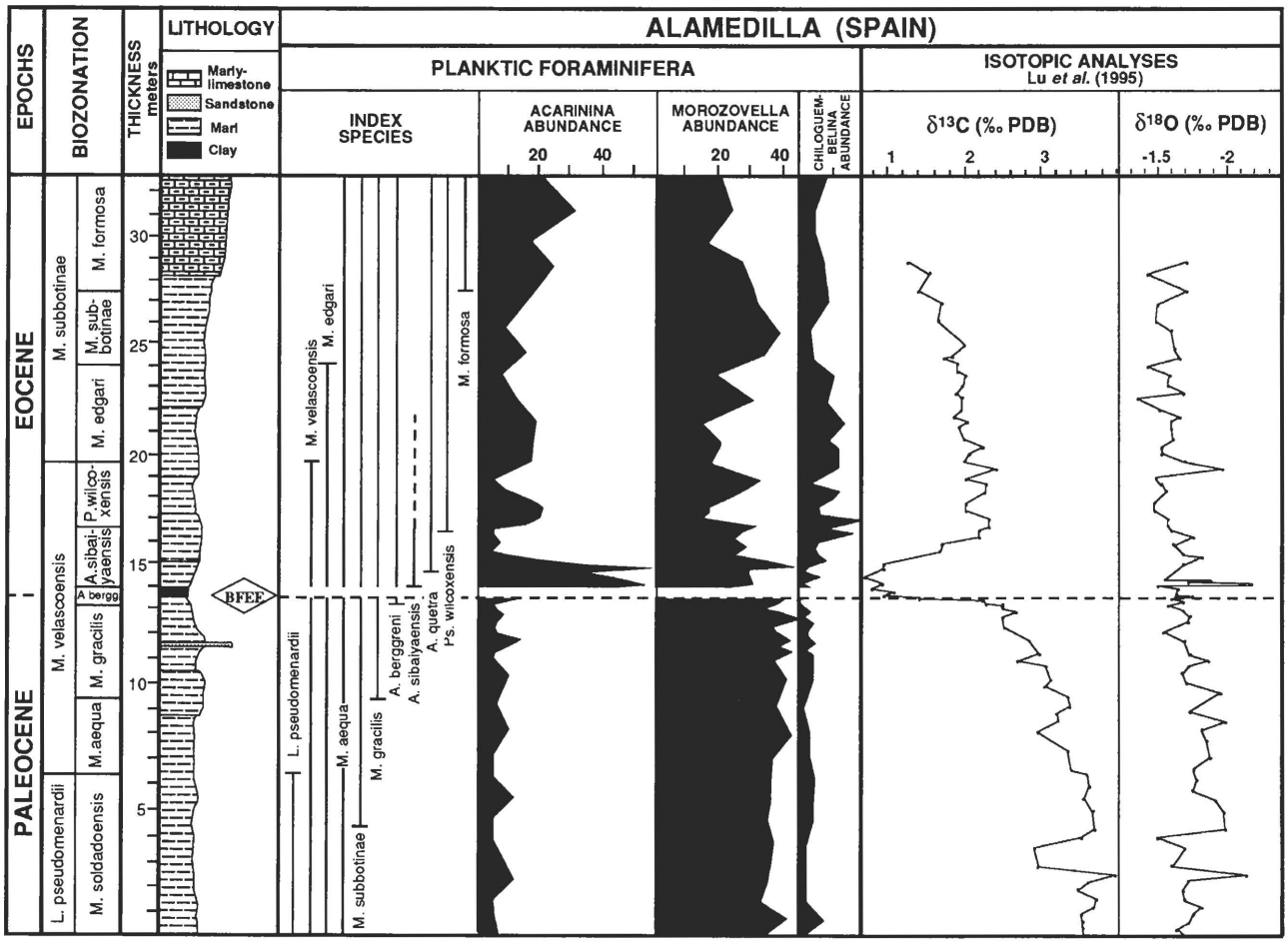

FIG. 3. – Biostratigraphy, quantitative and isotopic analyses at Alamedilla section.

FIG. 3. – *Biostratigraphie, analyses quantitative et isotopique dans la coupe d'Alamedilla.*

was used by Canudo and Molina [1992a,b] and is restricted here to its lowermost part. In this subzone *Morozovella lensiformis* first appears and *Subbotina velascoensis* and *Morozovella crosswickensis* disappear.

Morozovella subbotinae Zone

Biostratigraphic interval characterized by the partial range of the nominate taxon between the LO of *M. velascoensis* and the FO of *Morozovella aragonensis*.

This zone is equivalent to the Zone P6 of Berggren *et al.* [1995], the *Globorotalia subbotinae* Zone of Stainforth *et al.* [1975] and the lower part of the *Globorotalia rex (= M. subbotinae)* Zone of Bolli [1957]. This zone has been divided into the following subzones :

– *Morozovella edgari* Subzone. – Biostratigraphic interval between the LO of *M. velascoensis* and the LO of *M. edgari*. It was defined by Premoli Silva and Bolli [1973] and used by Toumarkine and Luterbacher [1985]. In this subzone *Igorina broedermanni* first appears and *Morozovella occlusa*, *Morozovella parva* and *Morozovella acuta* disappear.

– *Morozovella subbotinae* Subzone. – Biostratigraphic interval between the LO of *M. edgari* and the FO of *Morozovella formosa*. It corresponds approximately to the *Globorotalia subbotinae* Subzone of von Hillebrandt [1965]. In this subzone *Planorotalites pseudoscitula* first appears and *Subbotina triangularis, Morozovella tholiformis* and *Morozovella lacerti* disappear.

– *Morozovella formosa* Subzone. – Biostratigraphic interval between the FO of *M. formosa* to the FO of *M. aragonensis*. It was defined by Bolli [1957]. In this subzone *Morozovella crater, Acarinina apressocamerata, Subbotina inaequispira* first appear and *Globanomalina luxorensis, Igorina lodoensis* and *Morozovella marginodentata* disappear.

SECTIONS AND CORRELATION

The Palaeocene-Eocene transition has been studied in many sections across the Tethys in western Europe and northern Africa. Some of the studied sections, due to their shallow-water facies, are poor in planktic foraminifera such as Oued Mezez (Tunisia), Knokke (Belgium), Zomet Telalim (Israel) or Tremp (Spain) and therefore a high resolution planktic foraminiferal biostratigraphy is difficult to apply. At Oued Mezez, for example, there is a development of phosphate rich sediments, which represents the P/E boundary event in shallow shelf facies of the southern Tethys. The correlation among the ten best sections studied, indicating the thickness of the different biozones in metres, inferred hiatuses and other characteristics in relation to the biostratigraphical and geochronological time scale is shown in figure 2.

The Alamedilla section is probably the best exposed and most continuous section in Spain known so far. The preservation is not as good as in Caravaca, but planktic foraminifera are abundant, allowing a detailed biostratigraphy [Arenillas and Molina, 1996] that has been correlated with the isotopic and sedimentary compositional changes [Lu *et al.*, 1996; Arenillas *et al.*, 1996; Molina *et al.*, 1996a; Pardo and Arenillas, 1996]. All the subzones from *M. soldadoensis* to *M. formosa* are present and there is no evidence of hiatuses across the P-E transition. A very distinctive red clay interval marks the BFEE at the bottom and the extra-tropical excursion at the top (fig. 3). Nannofossils and magnetostratigraphy are currently under study.

The Caravaca section consists of marls in the Upper Palaeocene, a dark grey clay at the P/E boundary and sandy limestones in the lower Eocene. The foraminiferal assemblages were first studied by von Hillebrandt [1974] who established a correlation between planktic and large benthic foraminifera. Later on, this section was evaluated as a potential P/E boundary stratotype by Molina *et al.* [1994] based on a high resolution and integrated stratigraphical study. Recently, the planktic foraminiferal assemblages have been restudied by Molina *et al.* [1996a] and Arenillas and Molina [1997]. Planktic foraminifera are very abundant and quite well preserved but this section is not optimal as a candidate stratotype for the P/E boundary, mainly because of the likely presence of a short hiatus 2.5 m below the BFEE.

The Zumaya section is a quite expanded section especially from the *M. subbotinae* Biozone which consists of about 120 m of marls and calcitic sandstones. Nevertheless, the P-E transition is marly and not so highly expanded. Von Hillebrandt [1965] first published the planktic foraminiferal biostratigraphy of this section. Planktic foraminiferal assemblages, faunal turnovers and bio-chronostratigraphy of the P-E transition were studied by Canudo and Molina [1992a], Canudo *et al.* [1995] and Molina *et al.* [1996b]. A high-resolution iridium, isotopic, nannofossil and foraminiferal correlation has been conducted by Schmitz *et al.* [1997]. This section is the most expanded continuous deep marine record known to date. The *A. berggreni* Subzone is almost 2 m thick and the *A. sibaiyaensis* Subzone is about 4 m thick (fig. 4).

The Campo section constitutes the parastratotype of the Ilerdian Stage and consists of platform facies at the base. The section is extremely expanded with a 500 m thick *M. subbotinae* Biozone. Although planktic foraminifera are scarce, their assemblages were studied by several authors [von Hillebrandt, 1965; Canudo *et al.*, 1989; Canudo, 1991; Arenillas and Molina, 1995]. Many other microfossil groups are abundant (e.g., alveolinids, nummulitids, ostracodes, dinoflagellates, etc.) and the integrated stratigraphy across the P/E boundary has been revised and refined by Molina *et al.* [1992] and Serra-Kiel *et al.* [1994].

The Tremp section is the stratotype of the Ilerdian stage and consists of a shallow marine transgressive-regressive megasequence intercalated within terrestrial facies. Planktic foraminifera are scarce and limited to the middle part of the section, which corresponds to the P-E transition. Planktic foraminiferal assemblages were studied by Gartner and Hay [1962], von Hillebrandt [1965], Blow [1979] and

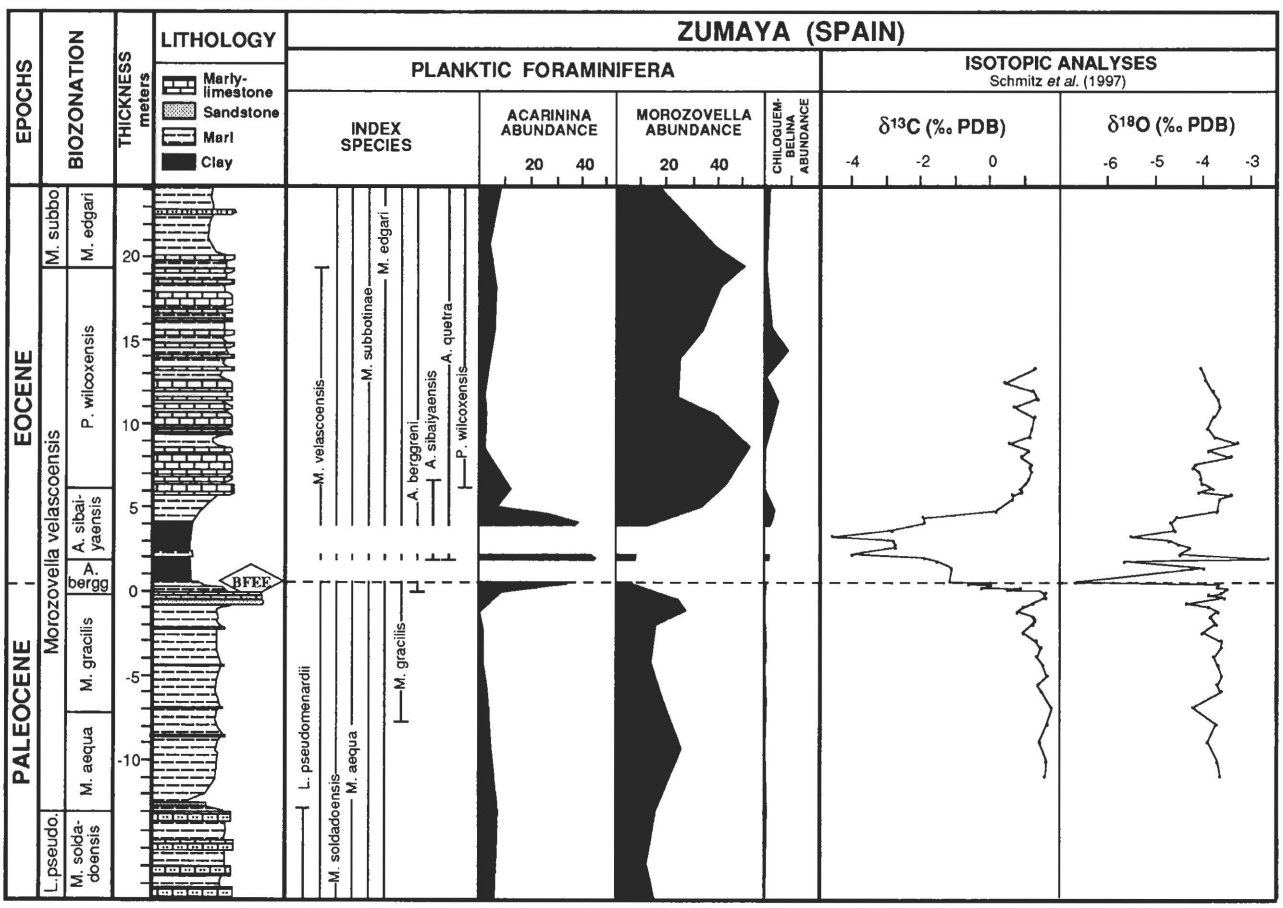

FIG. 4. – Biostratigraphy, quantitative and isotopic analyses at Zumaya section.

FIG. 4. – *Biostratigraphie, analyses quantitative et isotopique dans la coupe de Zumaya.*

Molina *et al.* [1992, 1995]. Both, the Tremp and Campo sections are very good reference sections to correlate shallow-water environments with deep sea settings.

DSDP Site 401 is located in the western abyssal plain of the Bay of Biscay. The P-E transition ranges from Zone P5 to P8, with some artificial hiatuses due to incomplete core recovery. Planktic foraminiferal assemblages show good preservation and diagenetic alteration is low. Analysis of $\partial^{13}C$ shows a shift coincident with a $\partial^{18}O$ shift, the BFEE and an increase in relative abundance of warm-water acarininids and morozovellids. After the BFEE and the isotopic shift, the chiloguembelinid population shows an increase, suggesting the onset of hypoxic conditions in intermediate waters [Pardo *et al.*, 1995, 1997].

The early micropalaeontological studies from the Possagno section (Italy) were summarized in a monograph, in which Luterbacher [1975] studied the planktic foraminifera. This classical Italian section is located in a quarry, which is a problem for considering it as a good candidate for the P/E boundary stratotype. Furthermore, the section is very condensed with a 4 cm thick dark red clay and about 1 m thick *Morozovella velascoensis* Zone. Nevertheless, we have recognized all the subzones from *M. aequa* to *P. wilcoxensis* Subzone. The acarininid extra-tropical excursion is very evident in coincidence with the $\partial^{13}C$ shift [Arenillas *et al.*, 1999] (fig. 5).

The Bottaccione section, located in Gubbio, is another classical Italian section. Planktic foraminiferal assemblages from the Palaeocene and lower Eocene were first studied by Luterbacher [1964]. Preservation of planktic foraminifera is poor since the lithology is very indurated and a slump prevents the study of most of the *L. pseudomenardii* Zone. Nevertheless, this section seems to be continuous across the P/E boundary. The nearby Contessa section in Gubbio is very similar to Bottaccione in lithology, thickness and poor preservation of planktic foraminifera, but it allows us to correlate more precisely the different biostratigraphical data. Both sections allow also to calibrate the planktic foraminiferal biostratigraphy with the magnetostratigraphy [Monechi and Thierstein, 1985; Arenillas, 1998].

Ben Gurion is one of the best Israeli sections. Planktic foraminifera are scarce below and frequent above the P/E boundary and were first studied by Benjamini [1980]. Several levels with scarcity or lack of planktic foraminifera are present across the P-E transition, which are probably due to the upwelling system along the southern margin of the Tethys [Lu *et al.*, 1995]. Two hiatuses have been recognized: the first hiatus affects the *A. sibaiyaensis* Subzone and the second hiatus the *M. edgari* Subzone. The absence of the *A. sibaiyaensis* Biozone hampers recognition of the typical acarininid excursion across the P/E boundary, only recognized in the *A. berggreni* Biozone just below the second hiatus. Nevertheless, the three zones from the *L. pseudomenardii* to the *M. subbotinae* Zone have been identified. The nearby Zomet Telalim section is more condensed and discontinuous than the Ben Gurion section and planktic foraminifera are even more scarce at Zomet Telalim [Arenillas, 1996].

The Kaurtakapy section, located in the boreal Paratethys, is a composite of two outcrops which are correlated by means of a 10 cm thick clay layer with marcasite nodules. Planktic foraminiferal assemblages are well preserved and

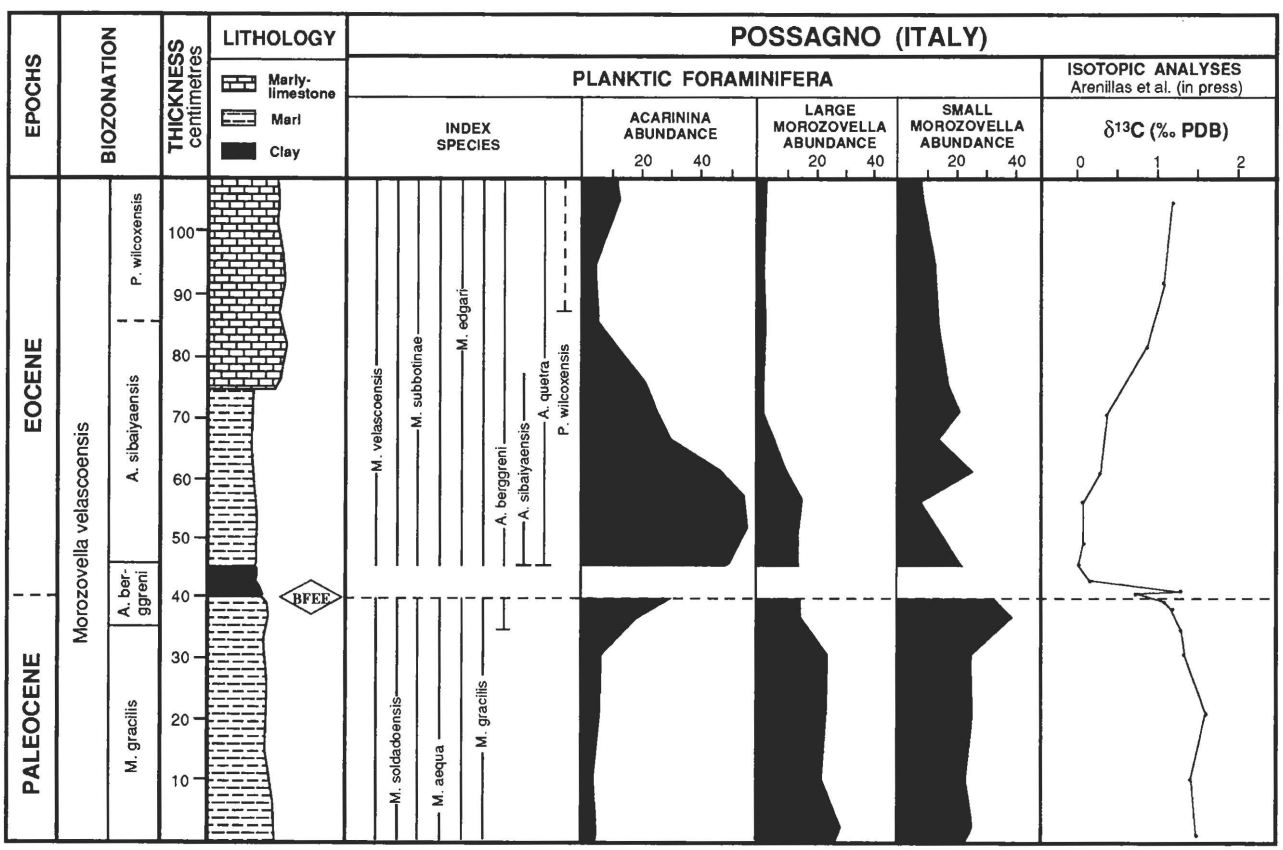

FIG. 5. – Biostratigraphy, quantitative and isotopic analyses at Possagno section.

FIG. 5. – *Biostratigraphie, analyses quantitative et isotopique dans la coupe de Possagno.*

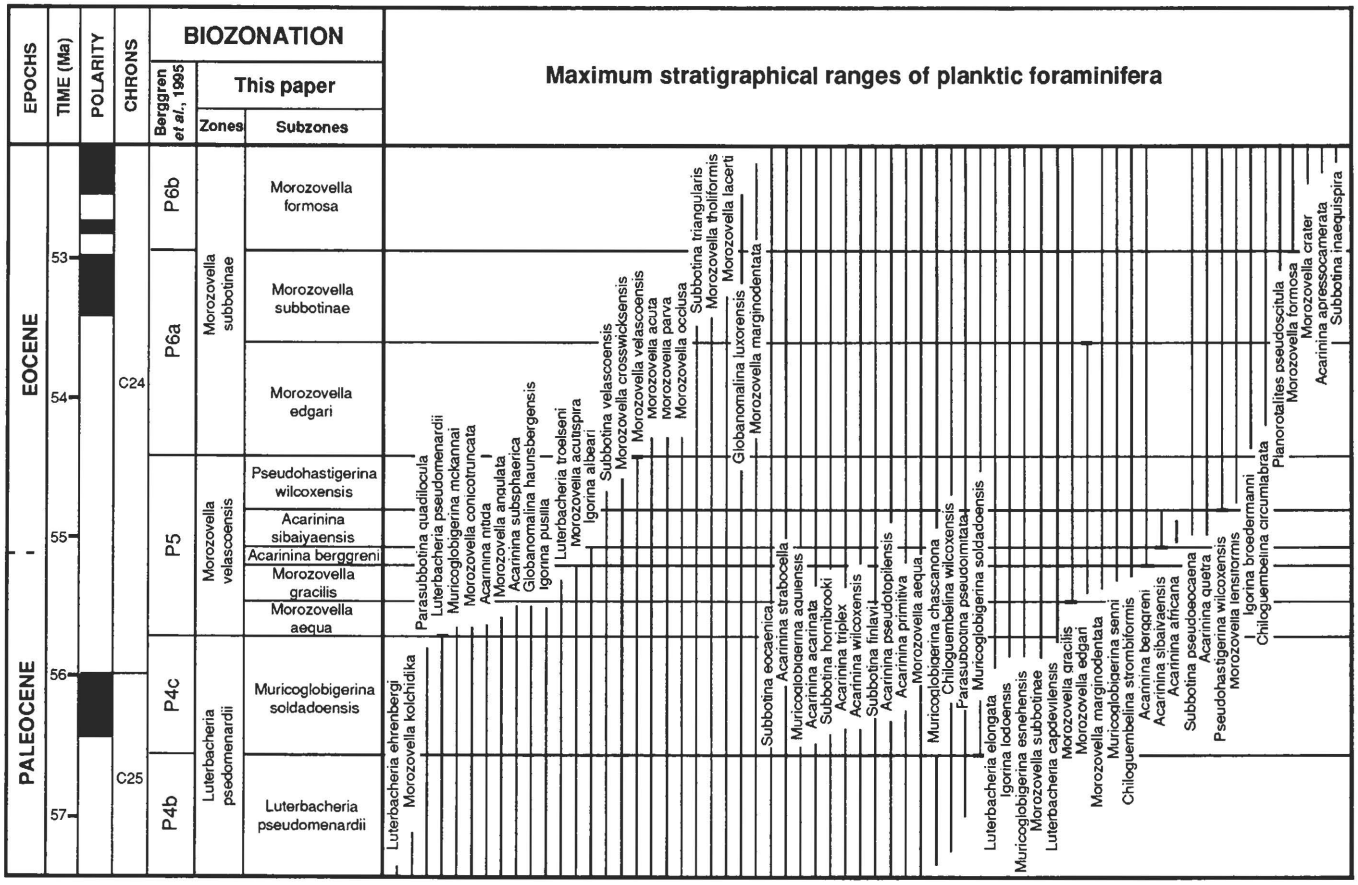

FIG. 6. – Maximun ranges of planktic foraminiferal species across the Tethys.

FIG. 6. – *Distribution stratigraphique des espèces des foraminifères planctoniques dans la Téthys.*

characterized by a sharp increase in relative abundance and species richness of tropical acarininids, morozovellids and igorinids during the P-E event. The maximum diversity of subtropical species and the FO of *Acarinina sibaiyaensis* and *A. africana* coincides with a $\partial^{13}C$ shift and the onset of the clay layer. Prior to the main $\partial^{13}C$ shift a long term gradual decrease characterizes the Upper Palaeocene [Pardo, 1998; Pardo and Arenillas, 1996; Pardo *et al.*, 1999]. The *A. sibaiyaensis* Subzone is only 0.4 m thick which suggests the presence of a hiatus comprising the *P. wilcoxensis* and *M. edgari* Subzones. Another possibility could be that the early disappearance of *A. sibaiyaensis* is due to the boreal influences and low temperature after the P/E event.

Other well known P/E boundary sections are Trabakua and Ermua located in northern Spain. The section of Trabakua has a very well developed red clay dissolution interval just above the BFEE, intercalated within limestones deposited in a distal plain. In contrast, the Ermua section represents a shallower environment and was situated at the base of a slope with a considerable amount of detrital flux and therefore the boundary clay is not developed [Orueetxebarria *et al.*, 1996]. Because of deep burial diagenesis and very poorly preserved microfossils, these two sections are not optimal potential stratotypes for the P/E boundary [Bolle *et al.*, 1998].

The correlation of the sections is easy and the high resolution biostratigraphy has allowed us to recognize several hiatuses (fig. 2). The general sedimentological sequence across the P/E boundary consists of a detrital unit (lowstand systems tract), a marl and a clay unit (transgressive systems tract) and a marly limestone unit (highstand systems tract), although the basal detrital unit, located in the *M. gracilis* Subzone, is not present in the condensed distal basin sections such as Possagno [Arenillas *et al.*, 1999].

The new subzonation is valid for subtropical and temperate latitudes where acarininids and morozovellids are frequent. The range of the species has been established based on the maximun stratigraphical distribution of each species considering all the sections studied (fig. 6). The new subzonation across the P/E boundary is easy recognizable in relatively deep pelagic sections located in Spain, Italy, Tunisia and Israel. On the contrary, it is more difficult to apply to sections with boreal influences such as Kaurtakapy (Kazakstan) in the northern Paratethys. In higher latitude sections most of the acarininids and morozovellids are only present in the interval of the extratropical excursion coincidental with the temperature rise. Consequently, the higher the latitude the less applicable the biozonation.

CONCLUSIONS

The study of various sections from northern Africa to northern Europe allows us to define a more detailed planktic foraminiferal biozonation valid for the low and middle latitudes of the Tethys. The three classical zones have been recognized across the P/E boundary: *Luterbacheria pseudomenardii* Biozone, *Morozovella velascoensis* Biozone and *Morozovella subbotinae* Biozone. The high resolution study allows us to define new subzones which are very detailed

especially across the P/E boundary. The *Morozovella velascoensis* Zone has been divided into the following subzones: *Morozovella aequa* Subzone, *Morozovella gracilis* Subzone, *Acarinina berggreni* Subzone, *Acarinina sibaiyaensis* Subzone and *Pseudohastigerina wilcoxensis* Subzone.

The isotopic and planktic foraminiferal excursions began at the base of the *Acarinina berggreni* Subzone and ended at the top of the *Acarinina sibaiyaensis* Subzone. The extinction of the bathyal and abyssal small benthic foraminifera has been found in the deep sea sections just below a dissolution clay interval. This relevant extinction event and the concomitant lithological change from marls to clay at bathyal and abyssal environments constitutes an apparently isochronous datum, which would be a very suitable criterion for the correlation of the P/E boundary. The BFEE occurs in the *Acarinina berggreni* Subzone. The planktic foraminiferal faunal turnover across the P/E boundary is quite gradual except at the BFEE horizon. *Acarinina berggreni* is the first acarininid to evolve related to the P/E boundary event and the FO of other new acarininids (*A. sibaiyaensis, A. africana* and *A. quetra*) is found at or just above the dissolution clay. This excursion indicates increased sea water temperatures coincident with the dissolution interval. An increase of the chiloguembelinid population has been found above the dissolution clay, when acarininid relative abundances and isotope ratios returned to normal values, indicating hypoxic conditions in intermediate waters.

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